Micro-Mirrors With Flexure Springs

BACKGROUND

[0001] Spatial light modulators (SLMs) are devices that modulate incident light in a spatial pattern to form an image corresponding to an electrical or optical input received by the SLM. The incident light may be modulated in phase, intensity, polarization, or direction. SLMs have numerous applications. For example, SLMs are currently used in the areas of projection displays, video and graphics monitors, televisions, optical information processing and electrophotographic printing.

[0002] An SLM is typically comprised of an array of individually addressable picture elements that correspond to the pixels in a frame of image data. A stream of image data is input to the SLM and each individual picture element is driven according to a corresponding pixel in a frame of the image data. The image data is thus displayed on the SLM one frame at a time

[0003] One type of SLM is a micro-mirror array in which each of the individually addressable picture elements is a microscopic mirror that can be moved according to the image data received. Conventional micro-mirror devices include an array of electro-statically actuated mirrors fabricated by CMOS (complementary metal-oxide-semiconductor) compatible processes over a memory cell on a silicon substrate. To meet the high frequency requirements for some video applications, the device must be able to drive each micro-mirror from one extreme landed position to another with a relatively high speed. This must be done while transition time and impact energy are minimized and operational robustness is maximized.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] The accompanying drawings illustrate various embodiments of the present invention and are a part of the specification. The illustrated embodiments are merely examples of the present invention and do not limit the scope of the invention.

[0005] Fig. 1 is a side view of a micro-mirror and flexure spring according to one embodiment.

[0006] Fig. 2 is a view of the underside the micro-mirror and flexure spring of Fig. 1.

[0007] Fig. 3 is an illustration of the mirco-mirror and flexure spring of Figs. 1 and 2 on a supporting substrate.

[0008] Fig. 4 is an illustration of a micro-mirror element according to another embodiment.

[0009] Fig. 5 is a graph showing the response time of the micro-mirror assembly of Fig. 3 as compared with micro-mirrors moved by torsion hinges.

[0010] Fig. 6 is a side view of a micro-mirror and flexure spring according to another embodiment.

[0011] Fig. 7 is a flowchart illustrating a method of making a micro-mirror and flexure spring according to one embodiment.

[0012] Throughout the drawings, identical reference numbers designate similar, but not necessarily identical, elements.

DETAILED DESCRIPTION

[0013] One current goal in micro-mirror design is to achieve a high transition speed for each individual micro-mirror. In other words, each micro-mirror needs to individually transition quickly from one angular position to another as incoming video data dictates. This is also referred to as the "crossover transition." A high crossover transition speed is needed for many digital display applications in which the micro-mirrors of the array must respond quickly to data for successive image frames.

[0014] The present specification describes a micro-mirror that is supported on a non-torsional flexure spring. When the micro-mirror is moved or tilted according to incoming video or image data, the pliant flexure spring stores potential energy caused by the movement of the micro-mirror against the bias of the flexure spring. This potential energy is converted to kinetic energy when the position of the micro-mirror is subsequently changed and serves to much more quickly reorient the micro-mirror. In other words, the mirror is driven by a flexure spring that stores enough elastic strain energy during a mirror tilting phase to significantly reduce the transition time in another direction through the efficient release of the stored strain energy as kinetic energy for crossover transition

[0015] Fig. 1 is a side view of a micro-mirror and flexure spring or pliant flexure according to the principles described herein. The micro-mirror (101) may be one in an array of micro-mirrors supported on a substrate (105). The substrate (105) may be, for example, a silicon, glass or plastic substrate.

[0016] Each individual micro-mirror (101) is supported on a non-torsional flexure spring (100) which will be described in more detail below. In a rest or default position, as shown in Fig. 1, the micro-mirror (101) is held by the flexure spring (100) in an orientation substantially parallel with the substrate (105).

[0017] The flexure spring (100) includes a post (104). A flexure (103) sits atop the post (104) and runs along the underside of the mirror (101). Two supports (102), at either end of the flexure (103), support the mirror (101) on the flexure (103) and separate the mirror (101) from the flexure (103). The post (104), flexure (103) and supports (102) can all be formed from a single layer of material. Alternatively, the supports (102) and the mirror (101) can be formed together from a second layer of material.

[0018] As shown in Fig. 1, drive circuitry (106) is provided to control the micro-mirror (101). The drive circuitry (106) may be formed on the substrate (105). The flexure spring (100) can be driven by the drive circuity (106) electrostatically or peizoelectrically, for example, to tilt the mirror (101) to a different angle with respect to the substrate (105). As indicated above, the

drive circuitry (106) will drive the micro-mirror (101) in response to incoming image data and, particularly, in response to the pixel data for a particular pixel that is represented by the micro-mirror (101) in the current image frame.

[0019] In the presently illustrated embodiment, electrodes (109) are formed on the substrate (105) under the flexure (103). In this embodiment, the drive circuitry (106) is electrically connected to and drives these electrodes (109) to create a particular electrostatic field. The flexure (103) will respond to the electrostatic field created by the electrodes (109) and tilt the mirco-mirror (101).

[0020] However, the flexure (103) also has a bias which, when the flexure spring (100) is not driven by the drive circuitry (106), causes the flexure spring (100) to hold the mirror (101) in a particular orientation with respect to the substrate (105). As shown in Fig. 1, this default orientation may be with the mirror (101) substantially parallel to the substrate (105).

[0021] As indicated, when the flexure spring (100) is driven by the drive circuitry (106), the flexure (103) bends to tilt the mirror (101) to a desired angular orientation. However, this motion is against the natural bias of the flexure (103). Thus, potential energy is stored in the flexure (103) while the flexure (103) and mirror (101) are driven out of the default orientation (e.g., Fig. 1) by the drive circuitry (106).

[0022] When the drive circuitry (106) stops driving the flexure (103), or if the signal from the drive circuitry (106) begins to drive the flexure (103) in a different direction, this potential energy is released as the flexure (103) moves with its bias to, or beyond, the default orientation. This release of potential energy and the bias of the flexure (103) cause the mirror (101) to reorient to a new desired orientation much more quickly than would be the case if the bias and potential energy of the flexure (103) were not assisting to move the mirror (101).

[0023] Fig. 2 is a view of the underside the micro-mirror and flexure spring of Fig. 1. As shown in Fig. 2, the flexure (103) of the flexure spring (100) may run diagonally between opposite corners of a square or rectangular micro-mirror (101).

[0024] The post (104) is located substantially in the center of the flexure (103). The supports (102) may be square (cubic) or rectangular in shape. Alternatively, the supports (102) may be round or circular in shape. With corners of the supports (102) being matched into corners of the mirror (101). The ends of the flexure (103) may also be pointed to match to the corners of the mirror (101) and supports (102).

[0025] Fig. 3 illustrates the mirror (101) and the flexure spring (100) formed or mounted on a substrate (105). As indicated above, the substrate (105) may be, for example, a silicon, glass or plastic substrate. The elements of the flexure spring (100) are illustrated in ghost to indicate being below or under the mirror (101).

[0026] Additionally, as shown in Fig. 3, the electrodes (109) are formed on the substrate (105) for driving the micro-mirror (101). Axis (110) is the axis about which the mirror (101) tilts. Separate electrodes (109) are formed on either side of the axis (110). Thus, as the electrodes (109) are driven by the drive circuitry (106, Fig. 1) to create an electrostatic field that will attract the flexure (103), the mirror tilts about the axis (110). In other words, the corners of the mirror (110) supported on the supports (102) move toward or away from the substrate (105) in response to the electrostatic field created by the electrodes (109).

[0027] Fig. 4 is similar to Fig. 3, but illustrates another embodiment in which additional flexures (106) are formed under the mirror (101). Thus, the flexure (103) may be formed as a plurality of flexures (106) extending from the post (104) along an underside of the micro-mirror (101). These additional flexures (106) make contact with the underside of the mirror (101) when the mirror (101) is driven. This is true whether the mirror is driven electrostatically or piezoelectrically. The additional flexures (106) are thus bent against bias by the tilting of the mirror (101). When the mirror (101) is no longer driven, the bias of the additional flexures (106) helps to more quickly return the mirror (101) to, or past, the default, undriven position.

[0028] Fig. 5 illustrates the results of modeling the improved response time of a micro-mirror supported on and driven by a flexure spring as described

herein and as compared to a conventional micro-mirror on a torsional spring or hinge. The vertical axis gives the angular orientation of the mirror, while the horizontal axis gives time in microseconds.

[0029] Trace (400) illustrates the response of a micro-mirror on a flexure spring as described herein. Trace (401) illustrates the movement of a micro-mirror on a conventional torsional spring or hinge. The traces (400 and 401) were generated using a 20 V square waveform.

[0030] As shown in Fig. 5, starting from a zero angular deflection, the micro-mirror with a flexure spring (trace 400) reaches an extreme negative deflection significantly faster than a conventional micro-mirror (trace 401). Even more dramatically, between 20 and 30 microseconds, the mirrors are switched from the extreme negative deflection to a positive deflection. The micro-mirror with a flexure spring (trace 400) is able to make the transition almost instantaneously, while the conventional mirror (trace 401) takes significantly longer. Thus, being driven in part by the flexure spring, the micro-mirror can be controlled more consistently and easily.

[0031] Fig. 6 illustrates another embodiment of a micro-mirror supported on a flexure spring. The flexture spring (100) in Fig. 6 is driven piezoelectrically rather than electrostatically. Accordingly, the electrodes (109, Fig. 1) on the substrate (105) are not required. Rather, the flexure (103-1) is formed as a piezoelectric unit that will flex when driven electrically. Thus, in this embodiment, the drive circuitry (106) is connected to the piezoelectric flexure (103-1).

[0032] When the drive circuitry (106) drives the flexure (103-1), the flexure (103-1) will bend against bias to tilt the mirror (101) in the same manner described above. An opposite current can be applied to opposite sides of the flexure (103-1) or the position of the piezoelectric materials can be reversed in opposite sides of the flexure (103-1), i.e., on opposite sides of the axis (110, Fig. 3). When the driving of the flexure (103-1) ceases, the natural bias of the flexure will help drive the mirror (101) back toward its default or rest orientation. As indicated above, a piezoelectrically driven embodiment can also optionally include the additional flexures (106) illustrated in Figure 4.

[0033] Some micro-mirrors operate in a dielectric liquid disposed on the substrate supporting the mirrors. The dielectric liquid magnifies the mirror tilting and reduces the activation voltage needed to operate the mirror. However, the induced fluid damping also prevents the mirror from being switched from one required tilt angle to another at high frequency (e.g., about 20 KHz).

[0034] The use of the flexure spring (100) described herein to support and drive a micro-mirror can also be used to support and drive a micro-mirror in a fluid. As a result, the action of the flexure spring helps overcome the drag of the fluid that damps movement of the mirror. Consequently, the micro-mirror can be oriented and re-oriented at a sufficiently high frequency while still enjoying the advantages provided by the use of the dielectric fluid. Also, as shown in Fig. 1, the micro-mirror (101) is positioned vertically away from the flexure (103) by the supports (102). This also helps reduce the fluid damping caused by operation in a dielectric fluid as the mirror (101) approaches either extreme angular position.

[0035] There are many advantages to supporting a micro-mirror on a flexure spring as described herein. For example, the flexures are less subject to fatigue failure than torsional hinges due to lower mechanical stress. Therefore, the micro-mirror design described herein should be more robust than designs that use torsional hinges. Additionally, the design described herein can reduce stress concentration problems in the mirror system so that larger electrostatic forces can be applied. This is accomplished by replacing short torsional hinges with the bending flexure springs which greatly reduces the induced stress in the system.

[0036] Additionally, with the flexure placed below the mirror no extra space is needed to accommodate the flexure. As indicated, the flexure spring can be actuated using electrostatic or piezoelectric forces and can store enough strain energy during a mirror tilting phase to significantly reduce the transition time to another mirror orientation through the efficient release of the stored strain energy as kinetic energy driving the crossover transition. The micro-mirror design described herein can be optimized to yield maximum extreme

angular position by varying the thickness, the electrostatic area (the flexures can have a non-uniform width), initial gap, and material properties of the flexures. .

[0037] An exemplary fabrication process for the electrostatically driven embodiment of Figs. 1-3 is illustrated in Fig. 7. As shown in Fig. 7, the fabrication process may begin with a 2-metal layer Static Random Access Memory (SRAM) cell (step 700). Next, a via is formed to electrically connect the SRAM cell to the flexure spring structure that will be formed (step 701).

[0038] A layer of metal material is then deposited to form an electrode in the via (step 702). This electrode will be used to operate the flexure spring and its micro-mirror. This layer of metal material is then exposed using photolithography (step 703) according to the pattern desired for the electrode, including the post (104, Fig. 1) of the flexure spring. The exposed layer of metal material is then etched to form the desired electrode (step 704). Next, the flex support via is formed from a sacrificial photoresist layer (step 705)

[0039] Another layer of material is then deposited (step 706). This layer is used to form post, flexure and supports of the flexure spring (100, Fig. 1). This layer is exposed using photolithography according to the pattern of the desired supports (step 707). The exposed layer is then etched to form the post and flexure (step 708). Then, a mirror support via is formed using a second sacrificial photoresist layer (step 709)

[0040] Next, a layer of material that will form the mirror (101, Fig. 1) is deposited (step 710). Using photolithography, this layer is next exposed according to the pattern of for the mirror (step 711). The exposed layer is then etched to form the mirror (step 712).

[0041] Finally, a Microelectromechanical System (MEMS) protection step is performed (step 713). The wafer or substrate is then sawn and mirror is etched to remove the sacrificial layers so that the mirror can move under the influence of the flexure spring (step 714). Finally, the completed unit is packaged for use (step 715).

[0042] The preceding description has been presented only to illustrate and describe embodiments of invention. It is not intended to be exhaustive or

to limit the invention to any precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be defined by the following claims.